

## **METHODS AND DEVICES COMPRISING SOLUBLE CONJUGATED POLYMERS**

### **STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH**

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### **TECHNICAL FIELD**

This invention relates to soluble conjugated polymers.

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### **BACKGROUND OF THE INVENTION**

Polymeric semiconductors have been incorporated into a wide array of  
electronic, optical and optoelectronic materials and devices. One limitation on  
manufacturing processes involving semiconducting polymers is the difficulties in  
preparing multilayer materials. Solution processing is one of the simplest, most  
15 economical, and most controllable methods for depositing layers of a conjugated  
polymer of interest. However, because most conjugated polymers are soluble in  
organic and/or nonpolar media, depositing a solution of one conjugated polymer onto  
a previously deposited layer of another conjugated polymer can solubilize it and result  
in interfacial mixing. This can lead to disruption of the desired device  
20 orientation/structure/geometry, process irreproducibility, and reduced efficiency of  
resulting devices. Thus traditional manufacturing methods for multilayer devices  
typically involve only one solution processing step for depositing polymers, with  
remaining layers deposited by more problematic methods, including sputtering,  
thermal vapor deposition, and chemical deposition methods, which can be more costly

and less controllable.

There is a need in the art for conjugated polymers having different physical properties, for methods of making and using them, and for compositions, articles of manufacture and machines comprising such compounds.

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## SUMMARY OF THE INVENTION

Methods, compositions and articles of manufacture involving soluble conjugated polymers are provided. The conjugated polymers have a sufficient density of polar substituents to render them soluble in a polar medium, for example water and/or methanol. The conjugated polymer may desirably comprise monomers which  
 10 alter its conductivity properties. In some embodiments, the inventors have provided cationic conjugated polymers (CCPs) comprising both solubilizing groups and conductive groups, resulting in conductive conjugated polymers soluble in polar media. The different solubility properties of these polymers allow their deposition in solution in multilayer formats with other conjugated polymers. Also provided are  
 15 articles of manufacture comprising multiple layers of conjugated polymers having differing solubility characteristics. Embodiments of the invention are described further herein.

## BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 depicts the HOMO (highest occupied molecular orbital) and LUMO  
 20 (lowest unoccupied molecular orbital) energy levels of poly(9,9-dioctylfluorenyl-2,7-diyl ("PFO")), poly(9,9-dihexyl-fluorene-co-benzothiadiazole) ("PFO-BT"), poly[2-methoxy-5-(2-ethyl-hexyloxy)-1,4-phenylene vinylene] ("MEH-PPV") and poly{[9,9-bis(6'-(N,N,N-trimethylammonium)hexyl)-fluorene-2,7-diyl]-alt-[2,5-bis(p-phenylene)-1,3,4-oxadiazole]} ("PFON<sup>+</sup>(CH<sub>3</sub>)<sub>3</sub>I-PBD") compared to the work  
 25 function of Ba (all referenced with respect to the vacuum).

Figure 2 shows the current density (mA/cm<sup>2</sup>) vs. applied voltage (V) and luminance (cd/m<sup>2</sup>) vs. applied voltage (V) for devices made using blue-emitting PFO with and without PFON<sup>+</sup>(CH<sub>3</sub>)<sub>3</sub>I-PBD as an electron-transport layer (ETL).

Figure 3 shows the luminous efficiency (cd/A) as a function of current density  
 30 (mA/cm<sup>2</sup>) for devices made with (a) PFO, (b) PFO-BT and (c) MEH-PPV with and

without ETL. Insets: (a) Power efficiency (lm/W) vs. bias (V) for devices made by PFO with and without ETL; (b) and (c) brightness ( $\text{cd/m}^2$ ) vs. current density ( $\text{mA/cm}^2$ ) for devices made by PFO-BT and MEH-PPV with and without ETL, respectively.

Figure 4 (a) and (b) are atomic force microscope (AFM) images show the surface of the ETL and that of the emissive polymer. The ETL layer provides an increased amount of features on the scale shown, providing more effective electron injection is achieved simply because of the increased contact area between ETL and cathode.

10 **DETAILED DESCRIPTION OF THE INVENTION**

The inventors have provided conjugated polymers having desirable properties. The conjugated polymers have a sufficient density of polar substituents to render them soluble in a polar medium. The polymers thus have desirable solubility properties allowing for their use with polymers of differing solubilities in methods involving multiple solution processing steps. The different solubility properties of these polymers allow their deposition in solution in multilayer formats with other conjugated polymers.

In some embodiments, the polar substituents can be charged groups, for example cationic or anionic groups. The conjugated polymers may have a sufficient density of solubilizing polar groups to render them soluble in a highly polar solvent such as water and/or methanol. This can be particularly advantageous for preparing multilayer polymeric devices via novel solution processing methods, also provided.

The conjugated polymer may desirably comprise monomers which alter its conductivity properties. The conjugated polymer can comprise monomers which improve its ability to inject and/or transport electrons. The conjugated polymer can comprise monomers which improve its ability to inject and/or transport holes. The conductivity of such polymers can be controlled through the type and/or amount of monomer(s) used, which may be selected to match with other materials of interest in electronic devices. The composition of the polymer may also be chosen to prevent conductivity of certain species. For example, the composition of the polymer may be

chosen so that it has hole-blocking properties, which can be desirable in certain device configurations, for example in polymer light-emitting diodes (PLEDs).

In some embodiments, the inventors have provided cationic conjugated polymers (CCPs) comprising both solubilizing groups and conductive groups,  
5 resulting in conductive conjugated polymers soluble in polar media. These conductive polymers are desirably soluble in water and/or lower alcohols, particularly methanol.

In some embodiments the CCPs can comprising monomers which perturb the polymer's ability to form rigid-rod structures, allowing them to form a greater range  
10 of three-dimensional structures. The monomers are aromatic molecules having attachment points to the adjacent subunits of the polymer which form an angle of greater than about 25° from linear. The monomers may introduce a torsional twist in the conjugated polymer, thereby further disrupting the ability of the polymer to form a rigid-rod structure.

Also provided are articles of manufacture comprising multiple layers of  
15 conjugated polymers having differing solubility characteristics. Multiple polymer layers produced by methods described herein can be incorporated in any of a variety of articles and machines.

Embodiments of the invention can comprise multiplex formats. For example,  
20 a plurality of different LEDs can be used simultaneously in a display format. Multiplex embodiments may employ 2, 3, 4, 5, 10, 15, 20, 25, 50, 100, 200, 400, 1000, 5000, 10000, 50000, 200000, one million or more distinct articles provided by one or more embodiments described herein. Other aspects of the invention are discussed further herein.

Before the present invention is described in further detail, it is to be  
25 understood that this invention is not limited to the particular methodology, articles, compositions or apparatuses described, as such methods, articles, compositions or apparatuses can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not  
30 intended to limit the scope of the present invention.

Use of the singular forms "a," "an," and "the" include plural references unless the context clearly dictates otherwise. Thus, for example, reference to "a conjugated

polymer” includes a plurality of conjugated polymers, reference to “a solvent” includes a plurality of such solvents, reference to “an LED” includes a plurality of LEDs, and the like. Additionally, use of specific plural references, such as “two,” “three,” etc., read on larger numbers of the same subject unless the context clearly  
5 dictates otherwise. The term “or” when used herein as the sole conjunction means “and/or” unless stated otherwise. The term “including” and related terms such as “includes” as used herein are not limiting and allow for the presence of elements in addition to those specifically recited.

Terms such as “connected,” “attached,” and “linked” are used interchangeably  
10 herein and encompass direct as well as indirect connection, attachment, linkage or conjugation unless the context clearly dictates otherwise.

Where a range of values is recited, it is to be understood that each intervening integer value, and each fraction thereof, between the recited upper and lower limits of that range is also specifically disclosed, along with each subrange between such  
15 values. The upper and lower limits of any range can independently be included in or excluded from the range, and all such ranges are encompassed within the invention. Where a value being discussed has inherent limits, for example where a component can be present at a concentration of from 0 to 100%, or where the pH of an aqueous solution can range from 1 to 14, those inherent limits are specifically disclosed as are  
20 ranges based on those inherent limits. Where a value is explicitly recited, it is to be understood that values which are about the same quantity or amount as the recited value are also within the scope of the invention, as are ranges based thereon with any other value as described herein.

Where a combination or group of elements is disclosed, each subset of those  
25 elements is also specifically disclosed and is within the scope of the invention. Conversely, where different elements or groups of elements are disclosed, combinations thereof are also disclosed.

Where any element of an invention is disclosed as having a plurality of alternatives, examples of that invention in which each alternative is excluded singly or  
30 in any combination with the other alternatives are also hereby disclosed; more than one element of an invention can have such exclusions, and all combinations of elements having such exclusions are hereby disclosed.

Unless defined otherwise or the context clearly dictates otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although any methods and materials similar or equivalent to those described herein can be used in the practice or testing of the invention, the preferred methods and materials are now described.

All publications mentioned herein are hereby incorporated by reference for the purpose of disclosing and describing the particular materials and methodologies for which the reference was cited. The publications discussed herein are provided solely for their disclosure prior to the filing date of the present application. Nothing herein is to be construed as an admission that the invention is not entitled to antedate such disclosure by virtue of prior invention.

#### DEFINITIONS

In describing the present invention, the following terms will be employed, and are intended to be defined as indicated below.

“Alkyl” refers to a branched, unbranched or cyclic saturated hydrocarbon group of 1 to 24 carbon atoms optionally substituted at one or more positions, and includes polycyclic compounds. Examples of alkyl groups include optionally substituted methyl, ethyl, n-propyl, isopropyl, n-butyl, s-butyl, t-butyl, n-pentyl, isopentyl, neopentyl, n-hexyl, n-heptyl, n-octyl, n-decyl, hexyloctyl, tetradecyl, hexadecyl, eicosyl, tetracosyl and the like, as well as cycloalkyl groups such as cyclopropyl, cyclobutyl, cyclopentyl, cyclohexyl, cycloheptyl, cyclooctyl, adamantyl, and norbornyl. The term “lower alkyl” refers to an alkyl group of 1 to 6 carbon atoms, preferably 1 to 4 carbon atoms. Exemplary substituents on substituted alkyl groups include hydroxyl, cyano, alkoxy, =O, =S, -NO<sub>2</sub>, halogen, haloalkyl, heteroalkyl, carboxyalkyl, amine, amide, thioether and -SH.

“Alkoxy” refers to an “-Oalkyl” group, where alkyl is as defined above. A “lower alkoxy” group intends an alkoxy group containing one to six, more preferably one to four, carbon atoms.

“Alkenyl” refers to an unsaturated branched, unbranched or cyclic hydrocarbon group of 2 to 24 carbon atoms containing at least one carbon-carbon

double bond and optionally substituted at one or more positions. Examples of alkenyl groups include ethenyl, 1-propenyl, 2-propenyl (allyl), 1-methylvinyl, cyclopropenyl, 1-butenyl, 2-butenyl, isobutenyl, 1,4-butadienyl, cyclobutenyl, 1-methylbut-2-enyl, 2-methylbut-2-en-4-yl, prenyl, pent-1-enyl, pent-3-enyl, 1,1-dimethylallyl, 5 cyclopentenyl, hex-2-enyl, 1-methyl-1-ethylallyl, cyclohexenyl, heptenyl, cycloheptenyl, octenyl, cyclooctenyl, decenyl, tetradecenyl, hexadecenyl, eicosenyl, tetracosenyl and the like. Preferred alkenyl groups herein contain 2 to 12 carbon atoms. The term "lower alkenyl" intends an alkenyl group of 2 to 6 carbon atoms, preferably 2 to 4 carbon atoms. The term "cycloalkenyl" intends a cyclic alkenyl 10 group of 3 to 8, preferably 5 or 6, carbon atoms. Exemplary substituents on substituted alkenyl groups include hydroxyl, cyano, alkoxy, =O, =S, -NO<sub>2</sub>, halogen, haloalkyl, heteroalkyl, amine, thioether and -SH.

"Alkenyloxy" refers to an "-Oalkenyl" group, wherein alkenyl is as defined above.

15 "Alkylaryl" refers to an alkyl group that is covalently joined to an aryl group. Preferably, the alkyl is a lower alkyl. Exemplary alkylaryl groups include benzyl, phenethyl, phenopropyl, 1-benzylethyl, phenobutyl, 2-benzylpropyl and the like.

"Alkylaryloxy" refers to an "-Oalkylaryl" group, where alkylaryl is as defined above.

20 "Alkynyl" refers to an unsaturated branched or unbranched hydrocarbon group of 2 to 24 carbon atoms containing at least one -C≡C- triple bond, optionally substituted at one or more positions. Examples of alkynyl groups include ethynyl, n-propynyl, isopropynyl, propargyl, but-2-ynyl, 3-methylbut-1-ynyl, octynyl, decynyl and the like. Preferred alkynyl groups herein contain 2 to 12 carbon atoms. The term 25 "lower alkynyl" intends an alkynyl group of 2 to 6, preferably 2 to 4, carbon atoms, and one -C≡C- triple bond. Exemplary substituents on substituted alkynyl groups include hydroxyl, cyano, alkoxy, =O, =S, -NO<sub>2</sub>, halogen, haloalkyl, heteroalkyl, amine, thioether and -SH.

"Amide" refers to -C(O)NR'R'', where R' and R'' are independently selected 30 from hydrogen, alkyl, aryl, and alkylaryl.

"Amine" refers to an -N(R')R'' group, where R' and R'' are independently selected from hydrogen, alkyl, aryl, and alkylaryl.

“Aryl” refers to an aromatic group that has at least one ring having a conjugated pi electron system and includes carbocyclic, heterocyclic, bridged and/or polycyclic aryl groups, and can be optionally substituted at one or more positions. Typical aryl groups contain 1 to 5 aromatic rings, which may be fused and/or linked.

5 Exemplary aryl groups include phenyl, furanyl, azolyl, thiofuranyl, pyridyl, pyrimidyl, pyrazinyl, triazinyl, biphenyl, indenyl, benzofuranyl, indolyl, naphthyl, quinolinyl, isoquinolinyl, quinazolinyl, pyridopyridinyl, pyrrolopyridinyl, purinyl, tetralinyl and the like. Exemplary substituents on optionally substituted aryl groups include alkyl, alkoxy, alkylcarboxy, alkenyl, alkenyloxy, alkenylcarboxy, aryl,  
10 aryloxy, alkylaryl, alkylaryloxy, fused saturated or unsaturated optionally substituted rings, halogen, haloalkyl, heteroalkyl, -S(O)R, sulfonyl, -SO<sub>3</sub>R, -SR, -NO<sub>2</sub>, -NRR', -OH, -CN, -C(O)R, -OC(O)R, -NHC(O)R, -(CH<sub>2</sub>)<sub>n</sub>CO<sub>2</sub>R or -(CH<sub>2</sub>)<sub>n</sub>CONRR' where n is 0-4, and wherein R and R' are independently H, alkyl, aryl or alkylaryl.

“Aryloxy” refers to an “-Oaryl” group, where aryl is as defined above.

15 “Carbocyclic” refers to an optionally substituted compound containing at least one ring and wherein all ring atoms are carbon, and can be saturated or unsaturated.

“Carbocyclic aryl” refers to an optionally substituted aryl group wherein the ring atoms are carbon.

20 “Halo” or “halogen” refers to fluoro, chloro, bromo or iodo. “Halide” refers to the anionic form of the halogens.

“Haloalkyl” refers to an alkyl group substituted at one or more positions with a halogen, and includes alkyl groups substituted with only one type of halogen atom as well as alkyl groups substituted with a mixture of different types of halogen atoms. Exemplary haloalkyl groups include trihalomethyl groups, for example  
25 trifluoromethyl.

“Heteroalkyl” refers to an alkyl group wherein one or more carbon atoms and associated hydrogen atom(s) are replaced by an optionally substituted heteroatom, and includes alkyl groups substituted with only one type of heteroatom as well as alkyl groups substituted with a mixture of different types of heteroatoms. Heteroatoms  
30 include oxygen, sulfur, and nitrogen. As used herein, nitrogen heteroatoms and sulfur heteroatoms include any oxidized form of nitrogen and sulfur, and any form of nitrogen having four covalent bonds including protonated and alkylated forms. An



optionally substituted heteroatom refers to a heteroatom having one or more attached hydrogens optionally replaced with alkyl, aryl, alkylaryl and/or hydroxyl.

“Heterocyclic” refers to a compound containing at least one saturated or unsaturated ring having at least one heteroatom and optionally substituted at one or more positions. Typical heterocyclic groups contain 1 to 5 rings, which may be fused and/or linked, where the rings each contain five or six atoms. Examples of heterocyclic groups include piperidinyl, morpholinyl and pyrrolidinyl. Exemplary substituents for optionally substituted heterocyclic groups are as for alkyl and aryl at ring carbons and as for heteroalkyl at heteroatoms.

“Heterocyclic aryl” refers to an aryl group having at least 1 heteroatom in at least one aromatic ring. Exemplary heterocyclic aryl groups include furanyl, thienyl, pyridyl, pyridazinyl, pyrrolyl, N-lower alkyl-pyrrolo, pyrimidyl, pyrazinyl, triazinyl, tetrazinyl, triazolyl, tetrazolyl, imidazolyl, bipyridyl, tripyridyl, tetrapyridyl, phenazinyl, phenanthrolinyl, purinyl and the like.

“Hydrocarbyl” refers to hydrocarbyl substituents containing 1 to about 20 carbon atoms, including branched, unbranched and cyclic species as well as saturated and unsaturated species, for example alkyl groups, alkylidenyl groups, alkenyl groups, alkylaryl groups, aryl groups, and the like. The term “lower hydrocarbyl” intends a hydrocarbyl group of one to six carbon atoms, preferably one to four carbon atoms.

A “substituent” refers to a group that replaces one or more hydrogens attached to a carbon or nitrogen. Exemplary substituents include alkyl, alkylidenyl, alkylcarboxy, alkoxy, alkenyl, alkenylcarboxy, alkenyloxy, aryl, aryloxy, alkylaryl, alkylaryloxy, -OH, amide, carboxamide, carboxy, sulfonyl, =O, =S, -NO<sub>2</sub>, halogen, haloalkyl, fused saturated or unsaturated optionally substituted rings, -S(O)R, -SO<sub>3</sub>R, -SR, -NRR', -OH, -CN, -C(O)R, -OC(O)R, -NHC(O)R, -(CH<sub>2</sub>)<sub>n</sub>CO<sub>2</sub>R or -(CH<sub>2</sub>)<sub>n</sub>CONRR' where n is 0-4, and wherein R and R' are independently H, alkyl, aryl or alkylaryl. Substituents also include replacement of a carbon atom and one or more associated hydrogen atoms with an optionally substituted heteroatom.

“Sulfonyl” refers to -S(O)<sub>2</sub>R, where R is alkyl, aryl, -C(CN)=C-aryl, -CH<sub>2</sub>CN, alkylaryl, or amine.

“Thioamide” refers to -C(S)NR'R'', where R' and R'' are independently selected from hydrogen, alkyl, aryl, and alkylaryl.

“Thioether” refers to -SR, where R is alkyl, aryl, or alkylaryl.

“Multiplexing” herein refers to an assay or other analytical method in which multiple analytes can be assayed simultaneously.

“Optional” or “optionally” means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where said event or circumstance occurs singly or multiply and instances where it does not occur at all. For example, the phrase “optionally substituted alkyl” means an alkyl moiety that may or may not be substituted and the description includes both unsubstituted, monosubstituted, and polysubstituted alkyls.

## 10 CONJUGATED POLYMER SOLUBLE IN POLAR MEDIA

Conjugated polymers (CPs) soluble in polar media are provided and can be used in embodiments described herein. The CPs comprise polar groups as solubilizing functionalities linked to polymer subunits to increase polymer solubility in polar media. Any or all of the subunits of the CP may comprise one or more pendant solubilizing groups. Exemplary polar groups include those introducing one or more dipole moments to the CP, for example halides, hydroxyls, amines, amides, cyano, carboxylic acids, and thiols.

Preferably the polar groups are charged groups, more preferably cationic groups. Any suitable cationic groups may be incorporated into CCPs. Exemplary cationic groups which may be incorporated include ammonium groups, guanidinium groups, histidines, polyamines, pyridinium groups, and sulfonium groups.

The solubilizing functionality may be linked to the conjugated polymer backbone by a linker, preferably an unconjugated linker, for example alkyl groups, polyethers, alkylamines, and/or polyamines.

One synthetic approach to introducing a charged group into a conjugated polymer is as follows. A neutral polymer is first formed by the Suzuki coupling of one or more bis- (or tris- etc.) boronic acid-substituted monomer(s) with one or more monomers that have at least two bromine substitutions on aromatic ring positions. Bromine groups are attached to any or all of the monomers via linkers. Conversion to cationic water-soluble polymers is accomplished by addition of condensed trimethylamine, which replaces the pendant bromines with ammonium groups.

In some embodiments, the conjugated polymer may desirably comprise conductive monomers which alter the conductivity of the overall polymer, increasing its ability to transport an electrical species. For example, the conjugated polymer can comprise monomer(s) which improve its ability to inject and/or transport electrons.

5 The conjugated polymer can comprise monomer(s) which improve its ability to inject and/or transport holes. More than one type of conductive monomer can be incorporated in the conjugated polymer. The conductivity of such polymers can be controlled through the type and/or amount of monomer(s) used, which can be selected to provide an electronic configuration compatible with other materials of interest in a  
10 given electronic device.

The conductive monomers may be electron-deficient monomers or electron-rich monomers. Electron-deficient monomers can be used to increase the ability of the polymer to inject and/or transport electrons, and to improve its ability to serve as an electron-transport layer. Electron-deficient monomers include unsaturated and/or  
15 aromatic groups appropriately substituted with electron-withdrawing groups. A number of electron-deficient monomers are known in the art. Exemplary electron-deficient monomers include benzothiadiazole, oxadiazole, quinoxaline, cyano-substituted olefins, squaric acid, and maleimide.

Electron-rich monomers can be used to increase the ability of the polymer to  
20 inject and/or transport holes, and to improve its ability to serve as a hole-transport layer. Electron-rich monomers include unsaturated and/or aromatic groups appropriately substituted with electron-donating groups, for example alkyl groups. A number of electron-rich monomers are known in the art. Exemplary electron-rich monomers include 9,9-dialkylfluorenes, 2,5-dimethyl-1,4-phenylidene, 2,5-  
25 dioctyloxy-1,4-phenylidene, and terthiophenes.

The composition of the polymer can also be chosen to prevent conductivity of certain species. For example, the composition of the polymer can be chosen so that it has hole-blocking properties, which can be desirable in certain device configurations, for example in polymer light-emitting diodes (PLEDs).

30 In some embodiments the polymers can comprise angled linkers with a substitution pattern (or regiochemistry) capable of perturbing the polymers' ability to form rigid-rod structures, allowing them to have a greater range of three-dimensional

structures. The polymers can comprise at least three subunits with at least one angled linker, which may be internal and/or an end unit, and may comprise at least 4, 5, 6, 8, 10, 15, 20, 25 or more subunits. The polymers may comprise up to about 100, 200, 300, 500, 1000, 2000, 5000, 10000, 20000, 50000 or more subunits.

5       The angled linker(s) are optionally substituted aromatic molecules having at least two separate bonds to other polymer components (e.g., monomers, block polymers, end groups) that are capable of forming angles relative to one another which disrupt the overall ability of the polymer to form an extended rigid-rod structure (although significant regions exhibiting such structure may remain.) The  
10   angled linkers may be bivalent or polyvalent.

      The angle which the angled linkers are capable of imparting to the polymeric structure is determined as follows. Where the two bonds to other polymeric components are coplanar, the angle can be determined by extending lines representing those bonds to the point at which they intersect, and then measuring the angle  
15   between them. Where the two bonds to other polymeric components are not coplanar, the angle can be determined as follows: a first line is drawn between the two ring atoms to which the bonds attach; two bond lines are drawn, one extending from each ring atom in the direction of its respective bond to the other polymeric component to which it is joined; the angle between each bond line and the first line is fixed; and the  
20   two ring atoms are then merged into a single point by shrinking the first line to a zero length; the angle then resulting between the two bond lines is the angle the angled linker imparts to the polymer.

      The angle which an angled linker is capable of imparting to the polymer is typically less than about 155°, and may be less than about 150°, less than about 145°,  
25   less than about 140°, less than about 135°, less than about 130°, less than about 125°, less than about 120°, less than about 115°, less than about 110°, less than about 105°, less than about 100°, less than about 95°, less than about 90°, less than about 85°, less than about 80°, less than about 75°, less than about 70°, less than about 65°, less than about 60°, less than about 55°, or less than about 50°. The angled linker may form an  
30   angle to its adjacent polymeric units of about 25°, 30°, 35°, 40°, 45°, 50°, 60° or more. The angled linker may introduce a torsional twist in the conjugated polymer, thereby further disrupting the ability of the polymer to form a rigid-rod structure. For

angled linkers having an internally rotatable bond, such as polysubstituted biphenyl, the angled linker must be capable of imparting an angle of less than about 155° in at least one orientation.

For six-membered rings, such angles can be achieved through *ortho* or *meta* linkages to the rest of the polymer. For five-membered rings, adjacent linkages fall within this range. For eight-membered rings, linkages extending from adjacent ring atoms, from alternate ring atoms (separated by one ring atom), and from ring atoms separated by two other ring atoms fall within this range. Ring systems with more than eight ring atoms may be used. For polycyclic structures, even more diverse linkage angles can be achieved.

Exemplary linking units which meet these limitations include benzene derivatives incorporated into the polymer in the 1,2 or 1,3-positions; naphthalene derivatives incorporated into the polymer in the 1,2-, 1,3-, 1,6-, 1,7-, 1,8-positions; anthracene derivatives incorporated into the polymer in the 1,2-, 1,3-, 1,6-, 1,7-, 1,8-, and 1,9-positions; biphenyl derivatives incorporated into the polymer in the 2,3-, 2,4-, 2,6-, 3,3'-, 3,4-, 3,5-, 2,2'-, 2,3'-, 2,4'-, and 3,4'- positions; and corresponding heterocycles. The position numbers are given with reference to unsubstituted carbon-based rings, but the same relative positions of incorporation in the polymer are encompassed in substituted rings and/or heterocycles should their distribution of substituents change the ring numbering.

The CP can be a copolymer, and may be a block copolymer, a graft copolymer, or both. The solubilizing functionalities, the conductive subunits and/or the angled linkers may be incorporated into the CP randomly, alternately, periodically and/or in blocks.

Exemplary polymers which may form the backbone of the compounds of the present invention include, for example, polypyrroles, polyfluorenes, polyphenylene-vinylenes, polythiophenes, polyisothianaphthenes, polyanilines, poly-p-phenylenes and copolymers thereof. Other exemplary polymeric subunits and repeating units are shown in the accompanying tables.

**Table 1.** Typical aromatic repeat units for the construction of conjugated segments and oligomeric structures.

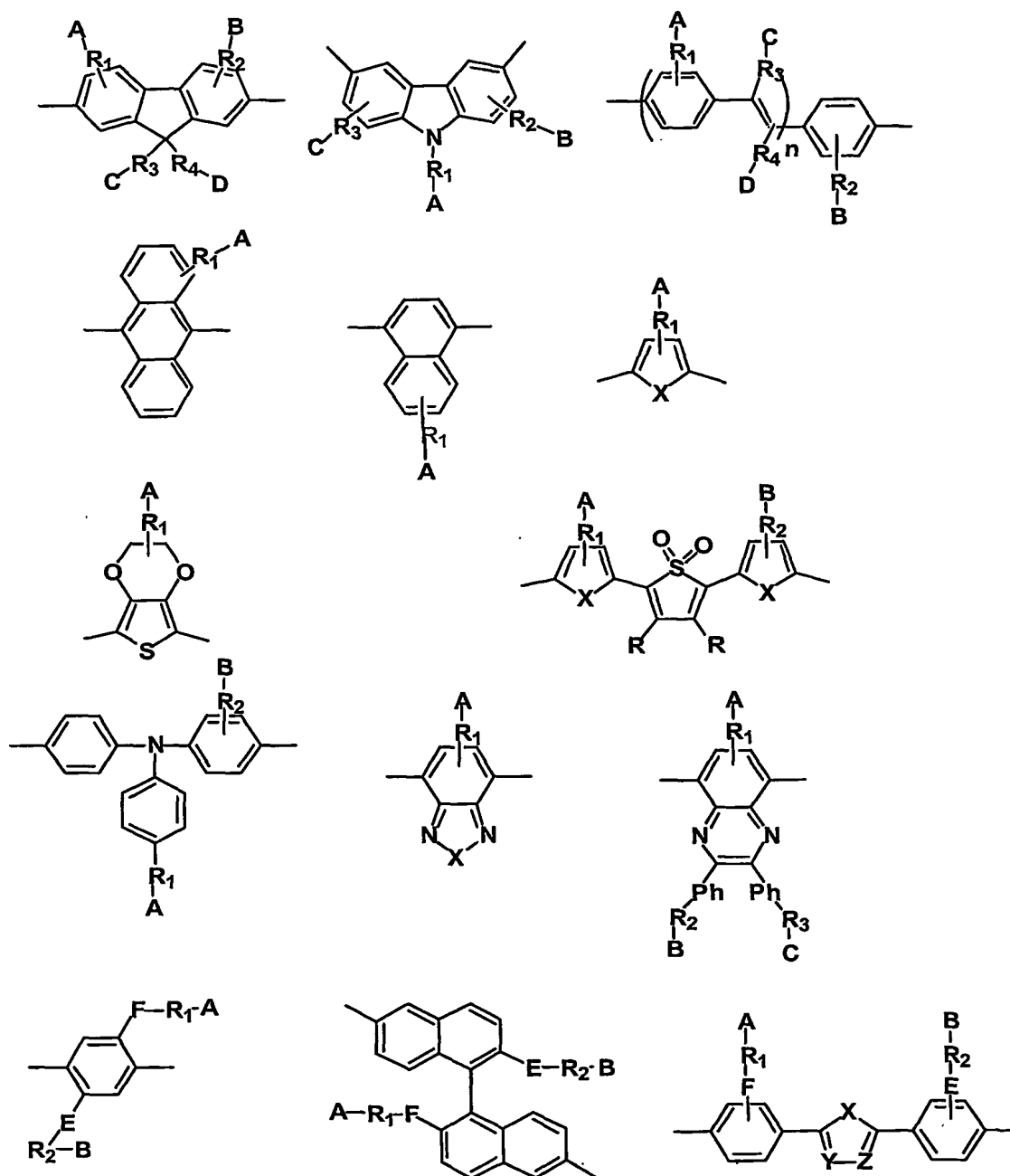
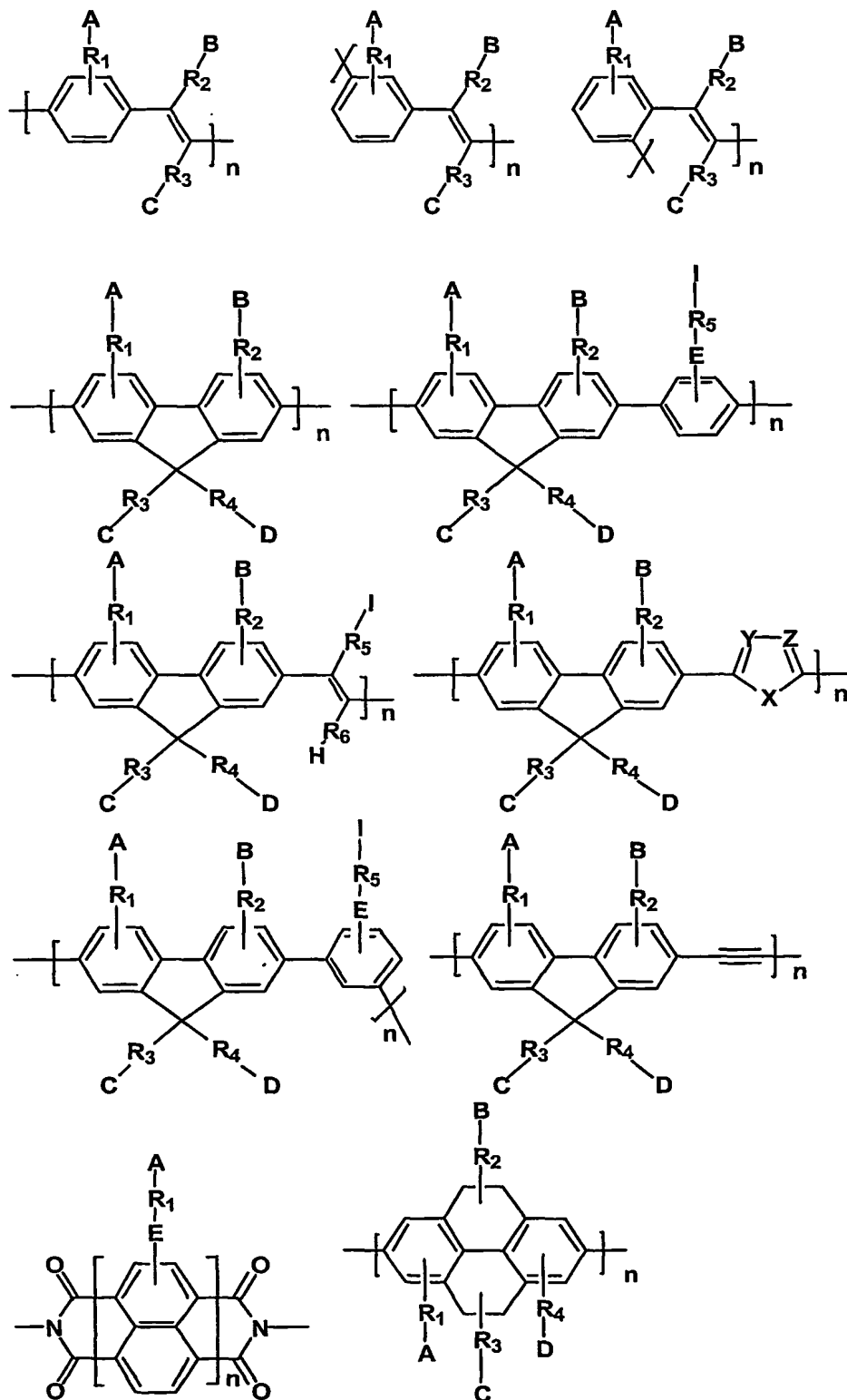
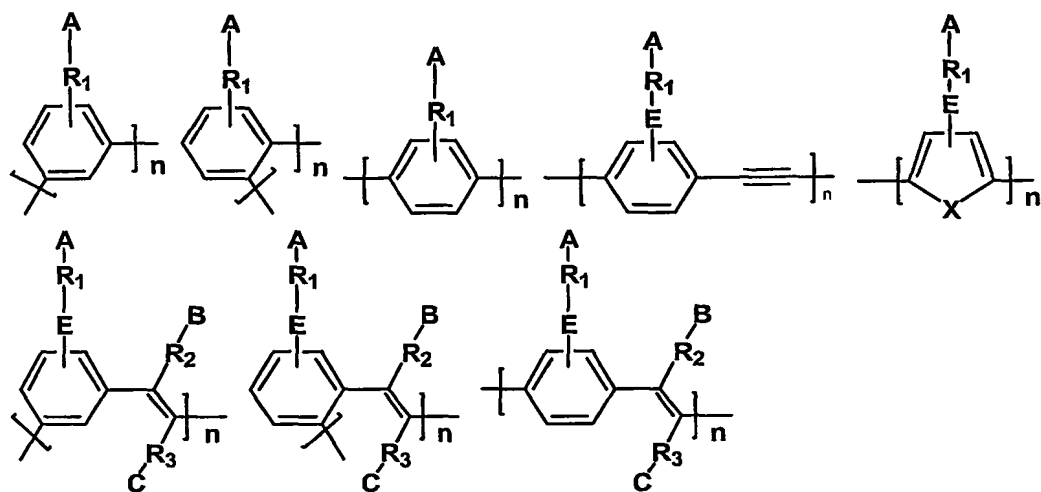
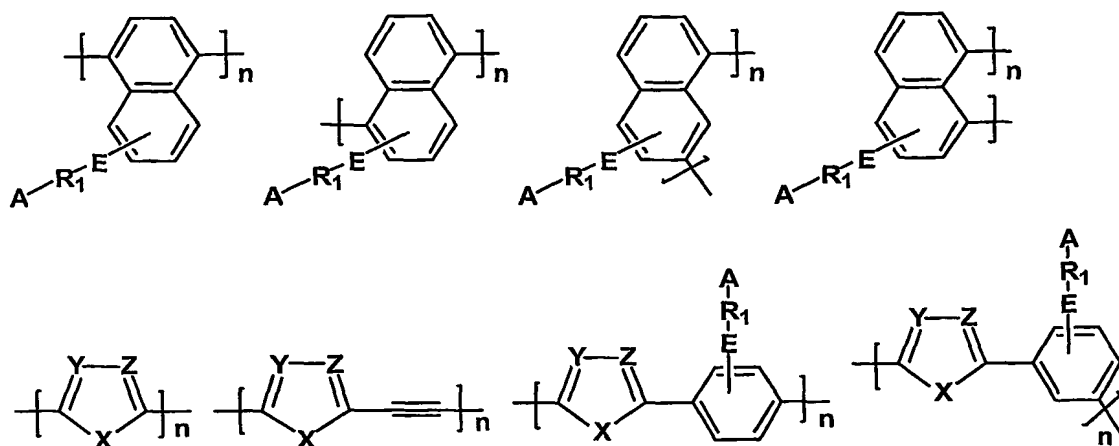


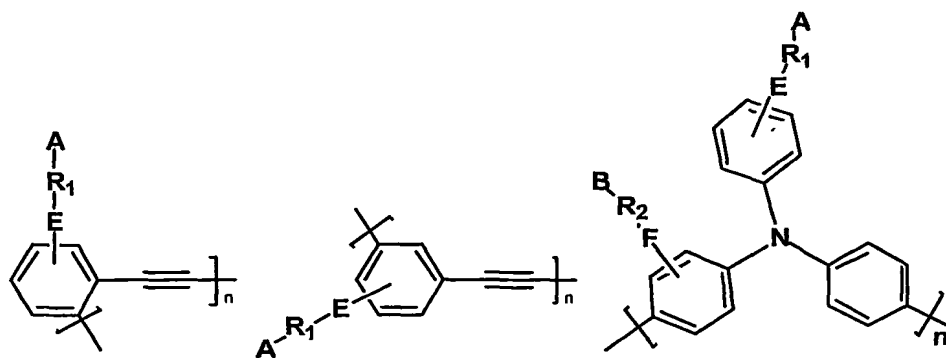
Table 2. Examples of conjugated segments and oligomeric structures of CP



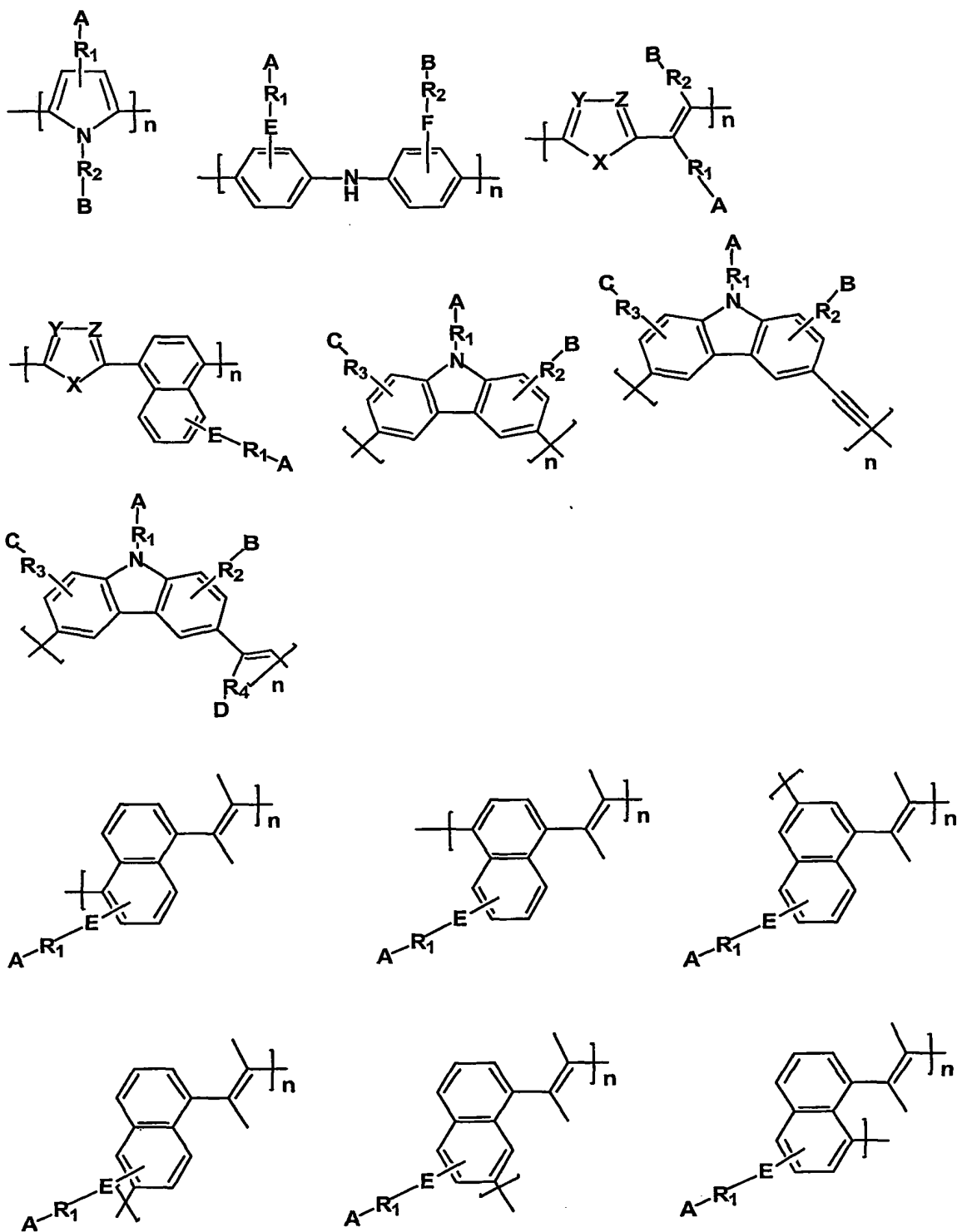
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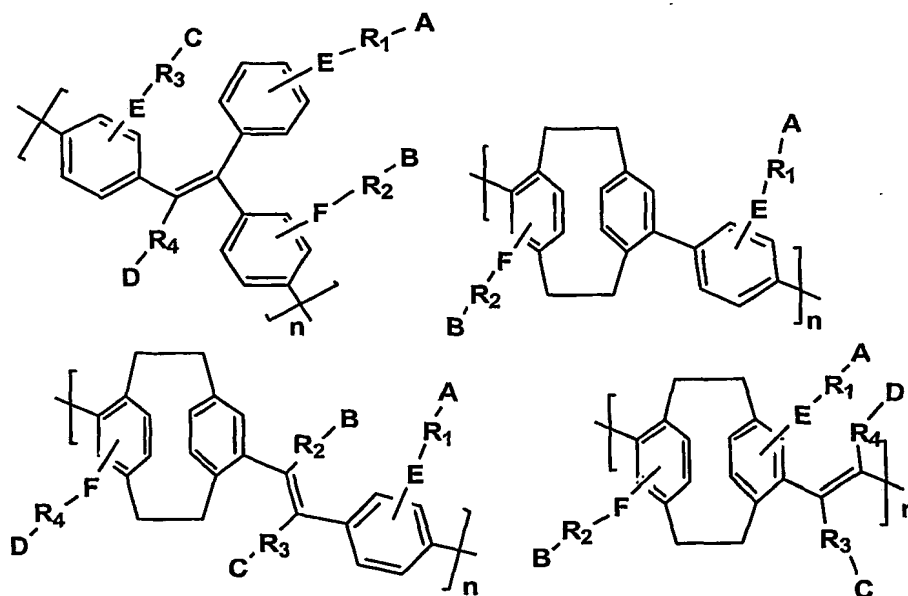


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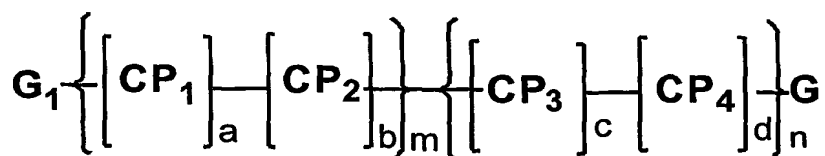
The CP contains a sufficient density of solubilizing functionalities to render the overall polymer soluble in a polar medium. The CP preferably contains at least about 0.01 mol % of the monomers substituted with at least one solubilizing functionality, and may contain at least about 0.02 mol %, at least about 0.05 mol %, at least about 0.1 mol %, at least about 0.2 mol %, at least about 0.5 mol %, at least about 1 mol %, at least about 2 mol %, at least about 5 mol %, at least about 10 mol %, at least about 20 mol %, or at least about 30 mol %. The CP may contain up to 100 mol % of the solubilizing functionality, and may contain about 99 mol % or less, about 90 mol % or less, about 80 mol % or less, about 70 mol % or less, about 60 mol % or less, about 50 mol % or less, or about 40 mol % or less.

The CP preferably contains at least about 0.01 mol % of the conductive monomers, and may contain at least about 0.02 mol %, at least about 0.05 mol %, at least about 0.1 mol %, at least about 0.2 mol %, at least about 0.5 mol %, at least about 1 mol %, at least about 2 mol %, at least about 5 mol %, at least about 10 mol %, at least about 20 mol %, or at least about 30 mol %. The CP may contain up to 100 mol % of the conductive monomers, and may contain about 99 mol % or less, about 90 mol % or less, about 80 mol % or less, about 70 mol % or less, about 60 mol % or less, about 50 mol % or less, or about 40 mol % or less.

The polymer may contain at least about 0.01 mol % of the angled linker, and may contain at least about 0.02 mol %, at least about 0.05 mol %, at least about 0.1 mol %, at least about 0.2 mol %, at least about 0.5 mol %, at least about 1 mol %, at least about 2 mol %, at least about 5 mol %, at least about 10 mol %, at least about 20 mol %, or at least about 30 mol %. The polymer may contain up to 100 mol % of the angled linker, and may contain about 99 mol % or less, about 90 mol % or less, about 80 mol % or less, about 70 mol % or less, about 60 mol % or less, about 50 mol % or less, or about 40 mol % or less.

Desirably, the CPs described herein are soluble in aqueous solutions and other highly polar solvents, and preferably are soluble in water. By "water-soluble" is meant that the material exhibits solubility in a predominantly aqueous solution, which, although comprising more than 50% by volume of water, does not exclude other substances from that solution, including without limitation buffers, blocking agents, cosolvents, salts, metal ions and detergents.

In one embodiment, an exemplary CCP is represented by Formula A:



**Formula A**

wherein:

CP<sub>1</sub>, CP<sub>2</sub>, CP<sub>3</sub>, and CP<sub>4</sub> are optionally substituted conjugated polymer segments or oligomeric structures, and may be the same or different from one another. CP<sub>1</sub>, CP<sub>2</sub>, CP<sub>3</sub>, and CP<sub>4</sub> may be aromatic repeat units, and may be selected from the group consisting of benzene, naphthalene, anthracene, fluorene, thiophene, furan, pyridine, and oxadiazole, each optionally substituted. Typical aromatic repeat units are shown in Table 1 below, and representative polymeric segments and oligomeric structures are shown in Table 2. One or more of CP<sub>1-4</sub> may be conductive monomers comprising electron-injecting and/or transporting properties or hole-injecting and/or transporting properties. The conductive monomers may be evenly or randomly

distributed along the polymer main chain.

CP<sub>1</sub>, CP<sub>2</sub>, CP<sub>3</sub> and CP<sub>4</sub> are each optionally substituted at one or more positions with one or more groups selected from -R<sub>1</sub>-A, -R<sub>2</sub>-B, -R<sub>3</sub>-C and -R<sub>4</sub>-D, which may be attached through bridging functional groups -E- and -F-, with the proviso that the  
5 polymer as a whole must be substituted with a plurality of cationic groups.

R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub> and R<sub>4</sub> are independently selected from alkyl, alkenyl, alkoxy, alkynyl, and aryl, alkylaryl, arylalkyl, and polyalkylene oxide, each optionally substituted, which may contain one or more heteroatoms, or may be not present. R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub> and R<sub>4</sub> can be independently selected from C<sub>1-22</sub> alkyl, C<sub>1-22</sub> alkoxy, C<sub>1-22</sub> ester,  
10 polyalkylene oxide having from 1 to about 22 carbon atoms, cyclic crown ether having from 1 to about 22 carbon atoms, or not present. Preferably, R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub> and R<sub>4</sub> may be selected from straight or branched alkyl groups having 1 to about 12 carbon atoms, or alkoxy groups with 1 to about 12 carbon atoms. It is to be understood that more than one functional group may be appended to the rings as indicated in the  
15 formulas at one or more positions.

A, B, C and D are independently selected from H, -SiR'R''R''', -N<sup>+</sup>R'R''R''', a guanidinium group, histidine, a polyamine, a pyridinium group, and a sulfonium group. R', R'' and R''' are independently selected from the group consisting of hydrogen, C<sub>1-12</sub> alkyl and C<sub>1-12</sub> alkoxy and C<sub>3-10</sub> cycloalkyl. It is preferred that R', R''  
20 and R''' are lower alkyl or lower alkoxy groups.

E and F are independently selected from not present, -O-, -S-, -C(O)-, -C(O)O-, -C(R)(R')-, -N(R')-, and -Si(R')(R''), wherein R' and R'' are as defined above.

X is O, S, Se, -N(R')- or -C(R')(R'')-, and Y and Z are independently selected from -C(R)= and -N=, where R, R' and R'' are as defined above.

25 m and n are independently 0 to about 10,000, wherein m + n > 1. Preferably m and n are each independently 0 to about 20 and more preferably from 0 to about 10. Each repeat of m and n may be the same as or different than the other repeats.

a, b, c and d are independently 0 to about 250. At least one of a, b, c and d must be greater than or equal to one.

G and G1 are capping units and may be the same or different. The capping units may be activated units that allow further chemical reaction to extend the polymer chain, or may be nonactivated termination units. G and G1 can be independently selected from hydrogen, optionally substituted aryl, halogen substituted aryl, boronic acid substituted aryl, and boronate radical substituted aryl.

Conjugated polymers may also be provided in purified form. Any available method or combination of methods may be used for purification. Exemplary methods include precipitation, extraction, and sublimation. Solutions of the CP are also provided. Solutions may be provided in a container of any suitable form. Solutions may be packaged in a container designed for incorporation into a solution processing apparatus, for example a printer. In some embodiments, the solution may be provided in an inkjet cartridge designed to be used with an inkjet printer.

#### THE POLAR SOLVENT

The conjugated polymer is soluble in a polar medium, a medium comprising at least one polar solvent. By "polar" is meant having a net dipole moment. Exemplary polar solvents include dimethylsulfoxide, dimethylformamide, formic acid, acetic acid, ethyl acetate, water, alcohols and polyalcohols, particularly lower alcohols (C<sub>1-4</sub>), particularly methanol. Preferably the polar solvent has a polarity of at least that of ethanol or ethyl acetate. In some embodiments, the polar solvent used to dissolve the CP is selected based on its inability to dissolve a second conjugated polymer onto which the CP is to be deposited.

The polar solvent in certain embodiments and solution formed therefrom in some embodiments is wettable on the surface to which it is to be applied, such that when it is deposited it flows generally uniformly and evenly over the surface, and preferably is controllable in thickness. Combinations of solvents may also be used.

- 5 Preferably the solvent is sufficiently wettable on the substrate that the solution spreads appropriately when deposited thereon. One or more wetting agents may be included in the solution to improve its ability to wet a surface and/or lowers its surface tension. For example, a solution comprising water may have an alcohol, a surfactant, or a combination of materials added thereto serving as wetting agents.

## 10 METHODS OF USE

- The CPs described herein can be used in a variety of methods. Methods of particular interest include deposition of the CPs into electronic devices, particularly in devices comprising multiple layers of conjugated polymers. Any of a variety of deposition methods can be used in a given device, including without limitation
- 15 vacuum sputtering (RF or Magnetron), electron beam evaporation, thermal vapor deposition, chemical deposition, sublimation, and solution processing methods. Any deposition method known or discoverable in the art can be used to deposit the soluble polar polymers provided herein, although solution methods are currently preferred.

- These layers are commonly deposited by spin-coating, drop-casting, sequential
- 20 spin-casting, formation of Langmuir-Blodgett films or electrostatic adsorption techniques.<sup>[28]</sup> Articles of manufacture may be fabricated by stepwise deposition of polymer layers; the water solubility of flexible CPs provided herein allows for the sequential deposition of layers of different materials with different solubilities, providing certain advantages during manufacturing, including for the deposition of
- 25 thin layers of material.

In particular embodiments, solution processing methods can be used to incorporate CPs into an article of manufacture. Printing techniques may advantageously be used to deposit the CPs, e.g., inkjet printing, offset printing, etc.

- Where the CPs are used in multilayer devices comprising multiple conjugated
- 30 polymeric layers, one or more of these layers may comprise nonpolar conjugated polymers which may not be soluble in a polar medium of interest. These include, for

example, MEH-PPV, P3ATs [poly(3-alkylthiophenes), where alkyl is from 6 to 16 carbons], such as poly(2,5-dimethoxy-p-phenylene vinylene)-“PDMPV”, and poly(2,5-thienylenevinylene); poly(phenylenevinylene) or “PPV” and alkoxy derivatives thereof; PFO, PFO-BT, and polyanilines. The nonpolar conjugated polymer can be deposited by any suitable technique; in some embodiments it is deposited or cast directly from solution. Typically, organic solvents are used, typically with low polarity. Exemplary organic solvents include: halohydrocarbons such as methylene chloride, chloroform, and carbon tetrachloride; aromatic hydrocarbons such as xylene, benzene, toluene; and other hydrocarbons including decaline.

Mixed solvents can also be used. The differing solubility properties of nonpolar and polar polymers allow for deposition of multiple polymeric layers via solution processing methods, which can simplify manufacturing and reduce costs. The water-soluble polymers described herein allow for the solution deposition of alternating layers of polymers of differing solubilities to form bilayer or multilayer devices.

When depositing the conjugated polymer on a substrate, the solution can be relatively dilute, such as from 0.1 to 20% w/w in concentration, especially 0.2 to 5% w. In some embodiments, film thicknesses may be at least about 50, 100, or 200 nm. In some embodiments, film thicknesses of less than about 400, 200, or 100 nm can be used.

The polymer solution can be formed into a selected shape if desired, e.g. a fiber, film or the like by any suitable method, for example extrusion.

After deposition of a solution comprising a conjugated polymer, the solvent is removed. Any available method or combination of methods may be used for removing the solvent. Exemplary solvent removal methods include evaporation, heating, extraction, and subjecting the solution to a vacuum.

In some embodiments, the conjugated polymer may be deposited on a substrate. The substrate can comprise a wide range of material, either biological, nonbiological, organic, inorganic, or a combination of any of these. In some embodiments, the substrate can be transparent. The substrate can be a rigid material, for example a rigid plastic or a rigid inorganic oxide. The substrate can be a flexible

material, for example a transparent organic polymer such as polyethyleneterephthalate or a flexible polycarbonate. The substrate can be conductive or nonconductive.

The CPs can be deposited on a substrate in any of a variety of formats. For example, the substrate may be a polymerized Langmuir Blodgett film, functionalized  
5 glass, Si, Ge, GaAs, indium doped GaN, GaP, SiC (Nature 430:1009, 2004), SiO<sub>2</sub>, SiN<sub>4</sub>, semiconductor nanocrystals, modified silicon, or any of a wide variety of gels or polymers such as (poly)tetrafluoroethylene, (poly)vinylidenedifluoride, polystyrene, cross-linked polystyrene, polyacrylic, polylactic acid, polyglycolic acid, poly(lactide coglycolide), polyanhydrides, poly(methyl methacrylate), poly(ethylene-  
10 co-vinyl acetate), polyethyleneterephthalate, polysiloxanes, polymeric silica, latexes, dextran polymers, epoxies, polycarbonates, agarose, poly(acrylamide) or combinations thereof. Conducting polymers and photoconductive materials can be used. The substrate can take the form of a photodiode, an optoelectronic sensor such as an optoelectronic semiconductor chip or optoelectronic thin-film semiconductor, or  
15 a biochip.

The CPs may be used in methods which screen the CPs for any property of interest. For example, the CPs may be tested for binding to a target, for energy transfer to a chromophore, for increased fluorescent efficiency, for decreased self-quenching, for absorbance wavelength, emission wavelength, conductive properties,  
20 ability to inject and/or transport electrons, ability to block holes, ability to inject and/or transport holes, and/or work function, etc.

#### ARTICLES OF MANUFACTURE

The CPs can be incorporated into any of various articles of manufacture including optoelectronic or electronic devices, biosensors, diodes, including  
25 photodiodes and light-emitting diodes ("LEDs"), optoelectronic semiconductor chips, semiconductor thin-films, and chips, and can be used in array or microarray form. The polymer can be incorporated into a polymeric photoswitch. The polymer can be incorporated into an optical interconnect or a transducer to convert a light signal to an electrical impulse. The CPs can serve as liquid crystal materials. The CPs may be  
30 used as electrodes in electrochemical cells, as conductive layers in electrochromic displays, as field effective transistors, and as Schottky diodes.



The CPs can be used as lasing materials. Optically pumped laser emission has been reported from MEH-PPV in dilute solution in an appropriate solvent, in direct analogy with conventional dye lasers [D. Moses, Appl. Phys. Lett. 60, 3215 (1992); U.S. Pat. No. 5,237,582]. Semiconducting polymers in the form of neat undiluted  
5 films have been demonstrated as active luminescent materials in solid state lasers [F. Hide, M. A. Diaz-Garcia, B. J. Schwartz, M. R. Andersson, Q. Pei, and A. J. Heeger, Science 273, 1833 (1996); N. Tessler, G. J. Denton, and R. H. Friend, Nature 382, 695 (1996)]. The use of semiconducting polymers as materials for solid state lasers is disclosed in U.S. Pat. No. 5,881,083 issued Mar. 9, 1999 to Diaz-Garcia et al. and  
10 titled "Conjugated Polymers as Materials for Solid State Lasers." In semiconducting polymers, the emission is at longer wavelengths than the onset of significant absorption (the Stokes shift) resulting from inter- and intramolecular energy transfer. Thus there is minimal self-absorption of the emitted radiation [F. Hide et al., Science 273, 1833 (1996)], so self-absorption does not make the materials lossy. Moreover,  
15 since the absorption and emission are spectrally separated, pumping the excited state via the  $\pi$  to  $\pi^*$  transition does not stimulate emission, and an inverted population can be obtained at relatively low pump power.

Light-emitting diodes can be fabricated incorporating one or more layers of CPs, which may serve as conductive layers. Light can be emitted in various ways,  
20 e.g., by using one or more transparent or semitransparent electrodes, thereby allowing generated light to exit from the device.

The mechanism of operation of a polymer LED requires that carrier injection be optimized and balanced by matching the electrodes to the electronic structure of the semiconducting polymer. For optimum injection, the work function of the anode  
25 should lie at approximately the top of the valence band,  $E_v$ , (the  $\pi$ -band or highest occupied molecular orbital, HOMO) and the work function of the cathode should lie at approximately the bottom of the conduction band,  $E_c$ , (the  $\pi^*$ -band or lowest unoccupied molecular orbital, LUMO).

LED embodiments include hole-injecting and electron-injecting electrodes. A  
30 conductive layer made of a high work function material (above 4.5 eV) may be used as the hole-injecting electrode. Exemplary high work function materials include electronegative metals such as gold or silver, and metal-metal oxide mixtures such as

indium-tin oxide. An electron-injecting electrode can be fabricated from a low work function metal or alloy, typically having a work function below 4.3. Exemplary low work function materials include indium, calcium, barium and magnesium. The electrodes can be applied by any suitable method; a number of methods are known to the art (e.g. evaporated, sputtered, or electron-beam evaporation).

In some embodiments, polymer light-emitting diodes have been fabricated using a semiconducting polymer cast from solution in an organic solvent as an emissive layer and a water-soluble (or methanol-soluble) conjugated copolymer as an electron-transport layer (ETL) in the device configuration: ITO(indium tin oxide)/PEDOT(poly(3,4-ethylene dioxythiophene)/emissive polymer/ETL/Ba/Al. The inventors have successfully fabricated multi-layer PLEDs using a semiconducting polymer (red, green or blue emitting), cast from solution in an organic solvent, as the emissive layer and a water-soluble (or methanol-soluble) cationic conjugated copolymer as electron-transport layer. The results demonstrate that devices with the ETL have significantly lower turn-on voltage, higher brightness and improved luminous efficiency.

Although the examples demonstrate the use of an electron-transport layer formed from the soluble conductive polymer, any form of conducting layer can be used. Thus, judicious choice of monomers as described herein can result in polymers with hole-injecting and/or transporting properties, as well as polymers with electron-injecting and/or transporting properties. The device geometry and deposition order can be selected based on the type of conductive polymer being used. More than one type of conductive polymer can be used in the same multilayer device. A multilayer device may include more than one layer of electron-injecting conjugated polymers, more than one layer of hole-injecting conjugated polymers, or at least one layer of a hole-injecting polymer and at least one layer of an electron-injecting conjugated polymer.

In PLEDs, the device efficiency is reduced by cathode quenching since the recombination zone is typically located near the cathode.<sup>[20]</sup> The addition of an ETL moves the recombination zone away from the cathode and thereby eliminates cathode quenching. In addition, the ETL can serve to block the diffusion of metal atoms, such as barium and calcium, and thereby prevents the generation of quenching centers<sup>[20]</sup> during the cathode deposition process.

In some embodiments, the principal criteria when a soluble conjugated polymer is used as an electron transport layer (ETL) in polymer light-emitting diodes (PLEDs) are the following: (1) The lowest unoccupied molecular orbital (LUMO) of the ETL must be at an energy close to, or even within the  $\pi^*$ -band of the emissive semiconducting polymer (so electrons can be injected); and (2) The solvent used for casting the electron injection material must not dissolve the underlying emissive polymer.

Similarly, the principal criteria for a polymer based hole transport layer (HTL) for use in polymer light-emitting diodes (PLEDs) is that the highest occupied molecular orbital (HOMO) of the HTL must be at an energy close to, or even within the valence band of the emissive semiconducting polymer.

Solubility considerations can dictate the deposition order of the particular CPs and solvents used to produce a desired device configuration. Any number of layers of CPs with different solubilities may be deposited via solution processing by employing these techniques.

The PLEDs comprising CPs described herein can be incorporated in any available display device, including a full color LED display, a cell phone display, a PDA (personal digital assistant), portable combination devices performing multiple functions (phone/PDA/camera/etc.), a flat panel display including a television or a monitor, a computer monitor, a laptop computer, a computer notepad, and an integrated computer-monitor systems. The PLEDs may be incorporated in active or passive matrices.

#### EXAMPLES

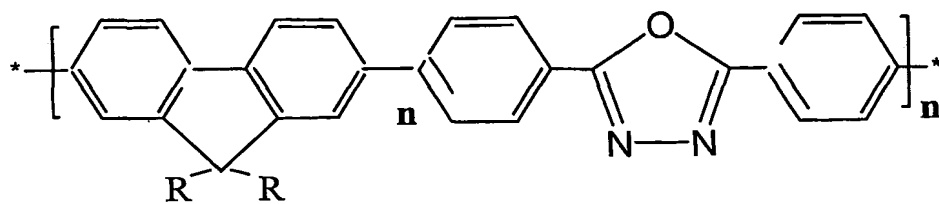
The following examples are set forth so as to provide those of ordinary skill in the art with a complete description of how to make and use the present invention, and are not intended to limit the scope of what is regarded as the invention. Efforts have been made to ensure accuracy with respect to numbers used (e.g., amounts, temperature, etc.) but some experimental error and deviation should be accounted for. Unless otherwise indicated, parts are parts by weight, temperature is degree centigrade and pressure is at or near atmospheric, and all materials are commercially available.

## Experimental

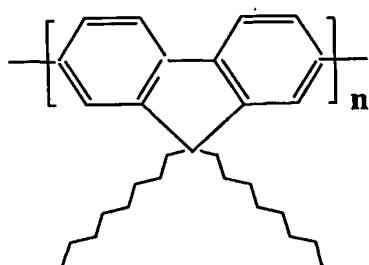
In one embodiment, polymer light-emitting diodes (PLEDs) have been fabricated using a semiconducting polymer cast from solution in an organic solvent as an emissive layer and a water-soluble (or methanol-soluble) conjugated copolymer as an electron-transport layer (ETL) in the device configuration: ITO/PEDOT/emissive polymers/ETL/Ba/Al. The results demonstrate that devices with the ETL have significantly lower turn-on voltage, higher brightness and improved luminous efficiency. See figures.

### Example 1. Fabrication of PLEDs

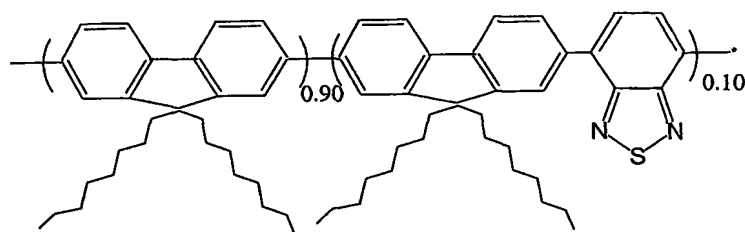
The water soluble conjugated copolymer, poly{[9,9-bis(6'-(N,N,N-trimethylammonium)hexyl)-fluorene-2,7-diyl]-*alt*-[2,5-bis(p-phenylene)-1,3,4-oxadiazole]}(PFON<sup>+</sup>(CH<sub>3</sub>)<sub>3</sub>I<sup>-</sup>-PBD) was synthesized using the palladium catalyzed Suzuki coupling reaction<sup>[13,14]</sup> and used as an electron transport layer (ETL). Poly(9,9-dihexyl-fluorene-*co*-benzothiadiazole) (PFO-BT) was also synthesized using the Suzuki coupling reaction.<sup>[15]</sup> Poly(9,9-dioctylfluorenyl-2,7-diyl) (PFO) and poly[2-methoxy-5-(2-ethyl-hexyloxy)-1,4-phenylene vinylene] (MEH-PPV) were purchased from American Dye Source, Inc. (Canada). The molecular structures of PFO, PFO-BT, MEH-PPV and PFON<sup>+</sup>(CH<sub>3</sub>)<sub>3</sub>I<sup>-</sup>-PBD are shown below:



**PFON<sup>+</sup>(CH<sub>3</sub>)<sub>3</sub>I<sup>-</sup>-PBD**



**PFO**

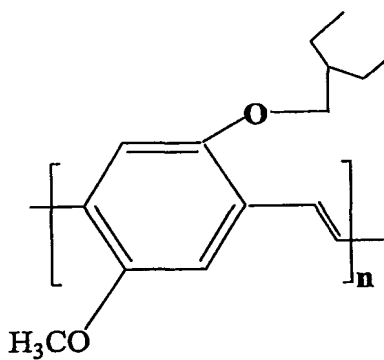


**PFO-BT**

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**MEH-PPV**

The HOMO (highest occupied molecular orbital) and LUMO energy levels are shown in Figure 1 (the work functions of poly(3,4-ethylene dioxythiophene):poly(styrene sulfonic acid) (PEDOT:PSS) and barium are also shown for comparison). PEDOT:PSS on indium tin oxide (ITO) was used as the hole-injecting bilayer electrode. PLEDs were fabricated with and without the ETL layer in the following device structures: (ITO)/PEDOT:PSS/Emissive polymer/Ba/Al and (ITO)/PEDOT:PSS/Emissive Polymer/ETL/Ba/Al. Details of device fabrication and testing have been reported elsewhere; all fabrication steps were carried out inside a controlled atmosphere dry box under nitrogen atmosphere.<sup>[16, 17]</sup> The ETL was deposited on top of the emissive layer by spin-casting from solution in methanol (0.6% wt.-%) to form a PFON<sup>+</sup>(CH<sub>3</sub>)<sub>3</sub>I<sup>-</sup>-PBD layer with thickness of approximately 30 nm and then annealed at 90°C for 2 hours to remove residual solvent. Hydrophilic methanol was used as the solvent (rather than water) to achieve better inter-layer wetting while maintaining well-defined multi-layers. The term "emissive polymer/ETL" is used to designate devices with an ETL.

## 15 **Example 2. Characterization of PLEDs Comprising a Water-Soluble CCP**

Figure 2 shows the current density vs. voltage and brightness vs. voltage characteristics of devices made using PFO with and without the ETL. The PFO/ETL devices turned on at ~3V (the turn-on voltage is defined as the voltage at the brightness of 0.1 cd/m<sup>2</sup>), whereas the turn-on voltage is at ~5V for PFO devices made without the ETL.<sup>[18]</sup> At 6 V, the luminance (L) obtained from the PFO/ETL devices is L = 3450 cd/m<sup>2</sup>, compared to L = 30 cd/m<sup>2</sup> for devices without the ETL.

Similar improvements were observed from the devices made with green and red emitting conjugated polymers. For MEH-PPV/ETL devices, L = 5600cd/m<sup>2</sup> at 5 V compared to L= 3550 cd/m<sup>2</sup> for similar devices fabricated without the ETL. Therefore, the addition of the ETL results in lower turn-on voltage and higher brightness.

The dramatic improvement in brightness and the reduced turn-on voltage result from improved electron injection (there is a good match of the LUMO of the ETL to the  $\pi^*$ -band of the emissive polymer(s)) and from the hole blocking capability of the ETL (LUMO energy at -6.24 eV relative to the vacuum).

The luminous efficiency (LE in cd/A) vs. current density (J in mA/cm<sup>2</sup>) for devices with and without the ETL are shown in Figure 3a, 3b and 3c. As shown in Fig. 3,

devices with ETL have higher luminous efficiency, higher power efficiency, and correspondingly higher brightness at a given voltage.

The improvements in LE and PE can be understood in greater detail by comparing the LUMO energy level of the emissive polymer with that of  $\text{PFON}^+(\text{CH}_3)_3\Gamma\text{-PBD}$  and the work-function of barium (see Figure 1). The energy barrier between the LUMO of PFO and the work function of barium is  $\sim 0.6$  eV. Thus, by adding the  $\text{PFON}^+(\text{CH}_3)_3\Gamma\text{-PBD}$  layer as the ETL, electron injection is enhanced.

For PFO-BT and MEH-PPV, there is no energy barrier for electron injection. However, the hole-blocking feature of the  $\text{PFON}^+(\text{CH}_3)_3\Gamma\text{-PBD}$  layer leads to better balanced electron and hole currents. In addition, the enhanced electron injection can also facilitate hole injection.<sup>[21]</sup> Therefore, the larger and more nearly balanced electron and hole currents lead to higher luminous efficiencies in the devices with the ETL.

Interfacial energetics are known to play an important role in the emission characteristics of organic LEDs.<sup>[22] [23]</sup> By adding the ETL between the cathode and the emissive polymer, the contacts at both interfaces are improved. Atomic force microscope (AFM) images show that the surface of the ETL is more rough than that of the emissive polymer. See Figure 4. As a result, more effective electron injection is achieved simply because of the increased contact area between ETL and cathode.

## Conclusion

The water- and methanol-soluble conjugated polymer,  $\text{PFON}^+(\text{CH}_3)_3\Gamma\text{-PBD}$ , was used as an electron-transporting layer in multi-layer PLEDs. By casting the ETL from solution in methanol and the emissive layer from solution in an organic solvent, interfacial mixing was avoided. Using blue, green or red emitting semiconducting polymers as the emissive layer and  $\text{PFON}^+(\text{CH}_3)_3\Gamma\text{-PBD}$  as the ETL, significant improvements in performance were demonstrated. More importantly, our results indicate that multi-layer PLEDs can be fabricated by deposition of multiple solutions.

Although the invention has been described in some detail with reference to the preferred embodiments, those of skill in the art will realize, in light of the teachings herein, that certain changes and modifications can be made without departing from the spirit and scope of the invention. Accordingly, the invention is limited only by the

5 claims.



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